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Electrical machine core imperfection detection

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Indexing terms: *Condition monitoring, Fault detection, Fault location, Generators, Motors*

Abstract: The paper describes the development of a core imperfection monitoring and detection system which eliminates the need for a high-voltage high-current excitation winding. The system is based on an electromagnetic testing technique. The paper reports a number of tests conducted in the United Kingdom and USA and gives comparisons of results made with the conventional ring flux test method and the new method. Accuracy of fault location and ease of implementation are discussed.

1 Introduction

Traditionally, the stator cores of large motors and generators have been tested for hot spots by installing an excitation winding to produce a circumferential ring flux around the core. This is invariably carried out with the rotor removed from the machine (see Fig. 1). Testing a large core would typically require several turns of 11 kV cable capable of carrying approximately 300 A. This would be wound through the bore and round the outside of the stator casing. For a 500 MW generator, this winding would then be connected to a supply of the order of 3 MVA to induce 80% of the normal operating flux density in the core.

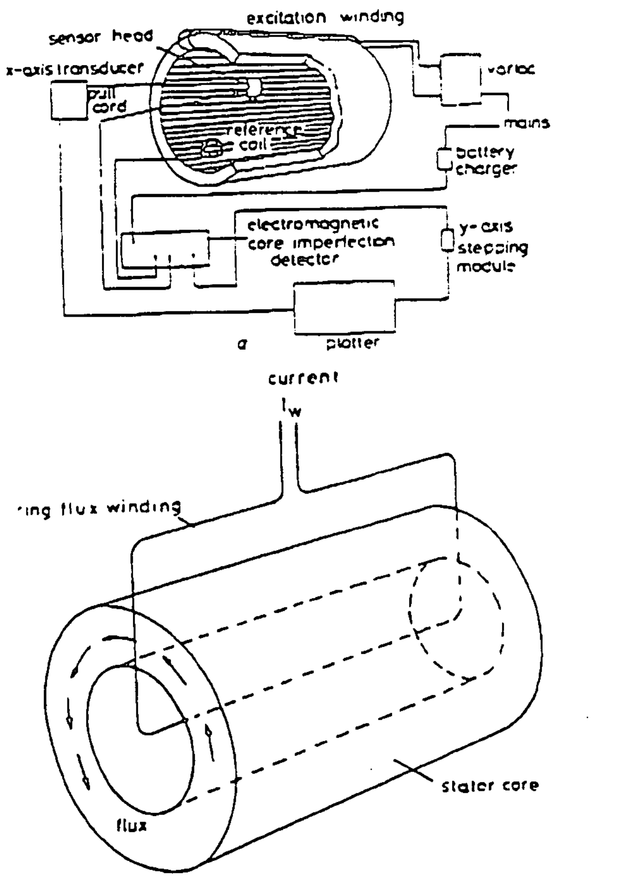

Fig. 1 *Schematic diagram for electromagnetic test method and arrangement for inducing flux*
a Schematic diagram for the electromagnetic test method
b Schematic arrangement for inducing flux

On smaller machines, once a high flux has been induced, operators are often known to attempt to detect heat rises derived from the circulating currents in the damaged laminations. By hand, obviously, the preferred method is to use infra-red camera techniques on critical or larger machines. The camera is used to scan along and around the bore surface, measuring the temperatures of the tips of the stator teeth. Surface damage may be readily apparent, but it is often very difficult to detect deep seated faults, and those below the coil windings. Typically, a deep seated fault may require up to an hour of excitation to produce temperature rises of sufficient magnitude to be detectable. As a consequence, this method is unlikely to indicate a major fault which is often missed due to resulting confusion brought about by the difficulty encountered in distinguishing between the deep seated fault and a minor surface fault. A large generator which may be six metres long, has typically a stack of some 200 000 individual steel laminations and each lamination should be insulated electrically from its neighbour. The whole stack is clamped together using the building bars. It is obviously vital to prevent unwanted currents being generated in the iron of the finished core. In the event of insulation breakdown between the laminations, serious overheating in the core can result.

This may, in turn, damage the winding and certainly affect the efficiency of the machine. Unfortunately, the insulation between laminations may also become damaged near the bore surface during assembly, or in operation, or maintenance, due to the inclusion of foreign bodies. In the event of this happening, a circuit may be completed through the damaged area, the laminations and the building bars. During operation, the rotating flux of the machine will then induce currents in this circuit which can lead to dangerous overheating or hot spots in the damaged areas as shown in Fig. 2. If allowed to persist, the hot spots

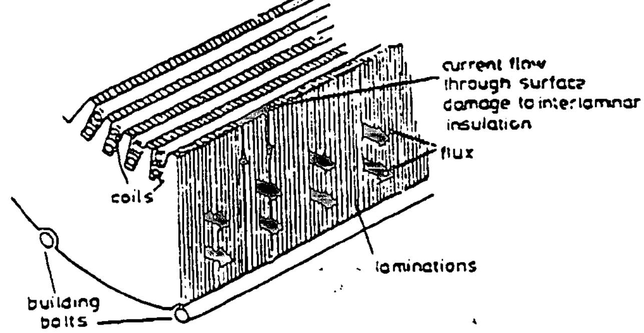

Fig. 2 *Induced currents in core fault*

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can damage the machine and cause electrical insulation, around the conductors in the stator winding, to deteriorate rapidly. Each time the winding insulation temperature is exceeded by as little as 10%, 50% of the insulation life is lost.

2 Description of monitoring system

To enable a rapid assessment of the state of a machine core and to make possible a rapid repair and return to service, an electromagnetic core imperfection detector was developed and is now used extensively throughout the UK power generation and the US power utilities. This system of fault detection is less cumbersome and provides a more sensitive test which enables the detection of potential hot spots electromagnetically. Its main advantage is that is is readily adaptable to field work as it requires only a low-voltage, low-current supply, even when used on the largest machine.

The winding itself requires only a few percent of the operating flux and induces very small currents through any damaged regions in the core. Consequently, any heating that is produced is insignificant, whereas with the conventional ring flux testing, the ring flux test itself may cause further damage as the machine is offline during test, and hence has no cooling.

The system described in this paper detects and measures the currents induced in a fault directly. Even if the damage is deep down in the slots between the stator teeth in the potentially dangerous position adjacent to winding insulation, detection is very simple. Apart from the obvious convenience of speed and sensitivity, if a fault is detected it is essential to be able to take some remedial action. The detection system uses a simple pick up coil which enables a measurement of the electromagnetic fields produced in the air by a current flowing along the iron surface. This coil may be left in place during a repair while laminations are separated, etched or ground, and the effect of the remedial action can thus be monitored in seconds.

The coil itself consists of a long thin solenoid with a double layer of fine wire uniformly wound on a flexible insulating former. The voltage induced in the coil is proportional to the line integral of the alternating magnetic field along its length. According to Amperes law, this integral along any closed path completely around a conductor, is equal to the current through that conductor. When the current is flowing along an iron surface, the magnetic intensity in the iron is much less than it is in the air, owing to the high relative permeability of the iron. Hence, the line integral of the magnetic intensity in the air is almost equal to the current, and the output voltage of the coil is a good measure of the current, when its two ends are placed on the iron bridging the circulating current within the laminations. The coil used for this purpose is known as a Chattock magnetic potentiometer and was invented in 1887 by Prof. Chattock. To use the Chattock sensing coil, the sensor is slid along the bore on the opposite corners of adjacent teeth, (with the two ends of the coil bridging the further corners of the teeth).

This enables any surface or deep imbedded fault to be encompassed and a diagnosis of its magnitude and position to be achieved. The arrangement for the connection of the potentiometer is shown in Fig. 3.

It is quite obvious that no rotating machine is perfect and even in the absence of any core damage, a large voltage is induced in the Chattock potentiometer spanning a pair of teeth. This voltage is due to the circumferential magnetic field from the exciting winding and in the case of a fault, the excitation flux is typically ten times larger than any fault current that might be detected. To enable a sensitive discrimination between the excitation flux and the flux

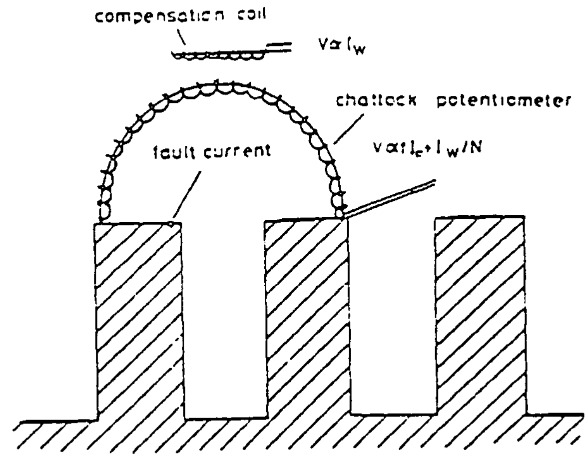

Fig. 3 *Test arrangement*
The Chattock potentiometer senses the MPD between teeth due to both the fault current (fI_f) and the excitation current (I_w/N). Much of the signal due to the latter is removed with the compensation coils. The fraction f is typically >0.5 and N is the number of stator teeth

induced from the circulating current in a fault, a compensation coil is placed approximately 50 mm above the tooth surface. This is subtracted from the Chattock potentiometer voltage and enables a 'first level' of discrimination to be achieved. Obviously, the complete elimination of the unwanted voltage induced by the excitation is not possible due to local variations in the permeability of the core. An arrangement for the potentiometer and compensation circuit is shown in Fig. 4. Fortunately, there is a phase

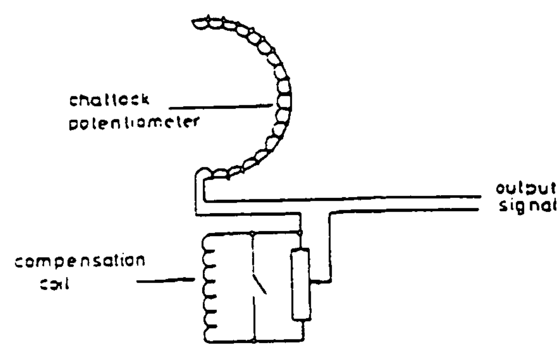

Fig. 4 *Circuit diagram of Chattock potentiometer and compensation coil*

shift between the excitation flux and those fluxes produced from circulating currents caused by faults, as previously indicated in Fig. 2.

The phase shift occurs because the circuit through which the fault current flows has a fairly high resistance and consequently is almost 90° out of phase with the main excitation.

By feeding the signal from the Chattock coil to the main processor of the equipment it is possible to eliminate the signal due to the excitation. This is done by using a phase-sensitive detector which measures the amplitude of the voltage from the potentiometer at the instant in time when the voltage induced by the winding current is zero.

A phase-sensitive detector, therefore, only requires one secondary input signal to give the phase of the magnetic field due to the winding current alone, and this is achieved using the reference coil in the bore of the machine. The reference coil has a magnetic base and can be clamped at

any convenient place within the bore. The flux rotating within the machine links the coil and induces a voltage proportional to it in magnitude and phase. This is then fed to the signal processor to enable the elimination of the unwanted excitation fluxes.

Once a circulating fault current has been detected, the voltage, which is directly proportional to this current, is amplified by several orders of magnitude, proportional to the alternating current flowing between the limbs of the potentiometer. This voltage is metered to enable the magnitude of faults to be measured. An output is also provided to enable a plotter or recorder to be used.

3 Basic theory of operation

As mentioned briefly in the preceding Section, the theory of operation is based on Amperes law, which states that for any closed loop of the line integral, the magnetic intensity is equal to the enclosed current I, i.e.

$$\oint H \cdot dl = I \tag{1}$$

If the current flows along an iron surface as shown in Fig. 4, eqn. 1 can be rewritten

$$\oint H \cdot dl = \int_{air} H \cdot dl + \int_{iron} H \cdot dl = I \tag{2}$$

As the permeability of the iron is very large compared with air, the field in the iron is much less than that in the air and therefore

$$\int_{air} H \cdot dl \sim I \tag{3}$$

Using a Chattock magnetic potentiometer, the difference in magnetic scalar potential between its two ends can be measured. If the ends are placed on an iron surface close to, but on opposite sides of, the current path, as shown in Fig. 3, the output voltage due to the current is

$$V = \mu_0 \omega n A I \tag{4}$$

where

μ_0 is the permeability of free space
ω the angular frequency of the current
n the number of turns per metre of the winding
A the cross-sectional area of the winding.

Here capital letters denote RMS values.

It is worth noting that the coil sensitivity is independent of its length and its path in air. The coil output is virtually the same as if it had completely encircled the conductor in air.

Even in the absence of any core damage, there is also a large magnetic potential difference due to the ampere turns I_w through the excitation winding. The value of I_w required to produce the electric field varies considerably between stators, being dependent on the initial permeability of the iron. As the circumferential flux is virtually constant around the core, the MMF of the winding $\pm I_w/2$ decays linearly around the core, provided that the permeability does not vary circumferentially. This result, depicted in Fig. 5, can be derived by solution of the Laplace equation for the magnetic potential. As most of the MMF is developed across the conductor slots, the magnetic potential at the teeth tips is almost constant and equal to the potential at the centre of a tooth. Hence the MMF between adjacent teeth, not enclosing the winding or carrying fault currents, is simply found: for example, if $I_w = 50$ A and $N \approx 50$, the MMF between adjacent teeth is ~ 1 A.

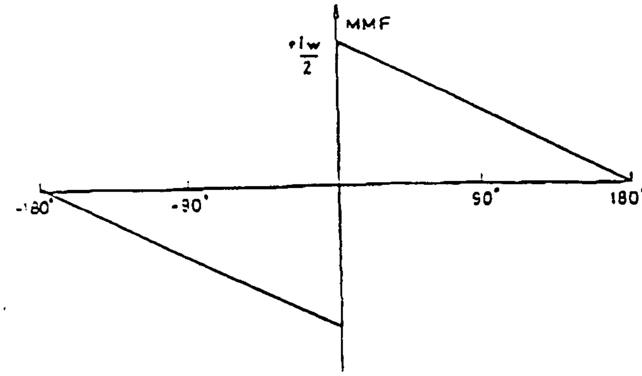

Fig. 5 *Variation in MMF around the core due to I_w ampere turns in the ring flux winding*

The instantaneous current may be represented by

$$I_w = \sqrt{2} I_w \sin \omega t \tag{5}$$

hence the instantaneous induced voltage around the whole core is

$$V_w = \sqrt{2} V_w \cos \omega t \tag{6}$$

where $V_w = I_w \omega L$, L being the inductance of a single turn winding around the core. The induced voltage across the damaged region is

$$V_f = \frac{l_f}{l_c} V_w \tag{7}$$

where l_f and l_c are the lengths of the damaged region and the whole laminated core, respectively. Representing the fault current through the damaged region by $I_F = \sqrt{2} I_F \cos(\omega t + \varepsilon)$ and solving for I_F and ε gives:

$$I_F = \sqrt{2} \frac{l_f}{l_c} V_w \left(\frac{R_F \cos \omega t + \omega L_F \sin \omega t}{R_F^2 + \omega^2 L_F^2} \right) \tag{8}$$

where R_F and L_F represent the resistance and inductance of the fault circuit respectively. Because the fault currents generate extra, noncircumferential, fluxes within the core the inductance per unit length L_F/l_f is much greater than that of the excitation winding whose flux is almost L_c/l_c, that of the excitation winding whose flux is almost entirely circumferential. Examination of eqn. 8 shows that if the fault current is low (i.e. $R_F \gg \omega L$), it is almost in phase quadrature with I_w and is therefore readily measured by the phase-sensitive detector which is set at 90°.

The reference signal to the phase-sensitive detector is derived from a coil in the bore which monitors the phase of the excitation current. The phase-sensitive detector is set to discriminate the signals in phase with respect to the reference. The output voltage due to the magnetic scalar potential difference due to the excitation winding, measured by the Chattock potentiometer is virtually eliminated. This enables small fault currents to be detected.

4 Operation of the detection system

To enable a fast and effective test on a motor or generator core, five turns of low current-capacity cable are wound through the stator bore around the outer casing of the machine, much in the same manner as used in a conventional test. However, the coil is only connected to a small variable transformer supplied from a convenient mains supply. This allows a small ring flux to be set up in the stator.

To enable a standard unit of measurement. the tests have been standardised to an excitation of 5 volts per metre of core length. To set this up in a convenient manner. one winding (a trace winding) is used in conjunction with the excitation and connected to a voltmeter. It is then a simple task to multiply the machine bore length in metres by five to enable the standard excitation of 5 V/m. The variac is then adjusted to give the appropriate level of excitation.

To test a complete bore. the sensing head is scanned along adjacent conductor slots. The sensor span is adjustable to be compatible on test with the distance between the corners of adjacent conductor teeth. The sensing head is traversed from one end of the machine to the other on consecutive teeth until the whole surface has been monitored. Careful note of meter deflection magnitudes and plotter readings are obviously important. A complete machine can be tested thoroughly in a few hours. and on a smaller motor a complete test can be carried out in approximately 30 minutes with the use of a prewound. pluggable excitation cable.

5 Interpretation of results

It is apparent that for a perfect machine. the measured responses would all be linear. However. in practice. there are minute irregular circulating currents all over a machine. Typically. these may give signals of magnitudes of the order of 15 mA. These are general background irregularities. However. a major fault often gives in excess of 1 A of signal and the position type and characteristic of the fault is readily observed. To illustrate the differences in response to various fault types. Fig. 6 shows a series of typical plotter recordings. It shows the outputs for three typical fault positions of equal magnitude.

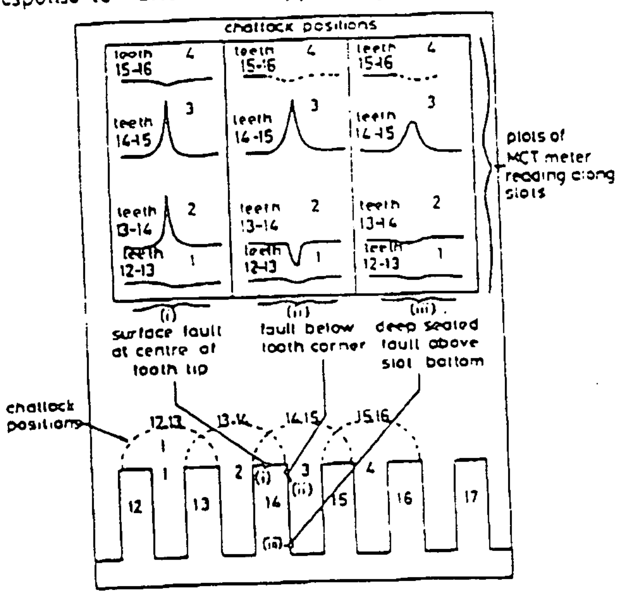

Fig. 6 Variation in response to typical faults

6 Assessment of the method compared with the conventional ring flux test

6.1 Advantages

(i) Excitation is much smaller allowing a low voltage. low ampere supply to be used as a supply for the test. This obviously improves the safety standards for operators and for the machine as it is impossible to damage the machine

(ii) Damaged regions of stators. which are normally repaired by grinding and etching to remove burrs. may be monitored in a few seconds. Alternatively. the conventional test would require the whole area to be cooled and then re-excited for up to an hour to see the progress of a repair. In addition. when a fault has been identified and a repair implemented. it may not be possible to carry out further tests. In practice. many instances have been reported where the repair appears cosmetically effective but in fact. upon subsequent examination it has been found that the fault condition has been exacerbated.

(iii) Deeply imbedded faults are readily detected and the magnitude of the fault is measurable. With the ring flux test. if the fault is detected. it is not obvious whether it is a minor fault near the surface or a major fault deep down under a conductor. However. with careful extrapolation. an estimate of the fault location may be made in certain circumstances. It is. however. difficult and involves considerable computation.

6.2 Comparison of tests based on field results

6.2.1 Test carried out on a 164 MW generator: In this test. a fault was simulated by damaging a small section of core approximately 1 cm down from a tooth tip. This fault was first recorded by a conventional ring flux test with an excitation of approximately 80% of rated flux induced. After 10 minutes. the temperature was measured in the vicinity of the fault. The criteria for judging a fault was standard in that a threshold of 5°C rise would just be tolerable on the specific location in the damaged area. An actual temperature rise of 7½° was detected. In comparative terms. this was 150% more than the minimum that would normally require remedial action.

On the test carried out by the system described in this paper. the criteria for judging a fault was standard in that a threshold of 100 mA pick up would be considered tolerable when 5 V/m of excitation is induced in the bore of a machine. When the system test was carried out under the same fault conditions. the trace shown in Fig. 7 was

Fig. 7 Response obtained from the monitoring system

obtained giving a pick up of 160 mA. With this test. there was obviously a good correlation as the threshold levels were exceeded by 50% on the ring flux test. and 60% on the system test.

6.2.2 Test carried out on 1640 MW generator: This test was carried out on a large generator manufactured in the USA in which the winding had been removed and a series of faults were introduced on the top of tooth tips and at the bottom of slots. The types of faults introduced ranged from hammer and chisel indentations. to the welding together of a packet of laminations between 1 cm and 3 cm long. Comparisons were then carried out using the developed monitoring system and the ring flux method.

In this series of trials. the developed system was attempted first. Once again. using a relatively small variac the faults were readily diagnosed. Interestingly. the hammer and chisel marks gave very little in the way of circulating current. It was also established that welding

over the same number of laminations at the base of the slot, was not quite so effective. At the time of conducting the test, this was thought to be unlikely, as on visual inspection the welding looked identical; however, this was later confirmed on the ring flux test and in one instance a minor fault detectable with the developed system was not detected at all with the conventional thermal imaging equipment. The conclusion, in this instance, was that the developed monitoring system is more sensitive than the core ring test. There was very good correlation between the results obtained with the two techniques. It was also concluded that when using the ring flux test in the presence of a large fault, the short-circuits themselves can create more short-circuits and hence a runaway condition, which could give rise to subsequent machine failure.

6.2.3 Test carried out on a UK machine returned from several years field duty (142 MW): This case illustrates a typical comparison of faults carried out on a machine in which a small fault had first been located by the ring flux technique. This correlated well with the results indicated by the monitoring system and indicated a fault magnitude of 0.26 A. An alarming situation also arose with this test, however. A major fault of 1.2 A went undetected with the conventional ring flux test (see Fig. 8).

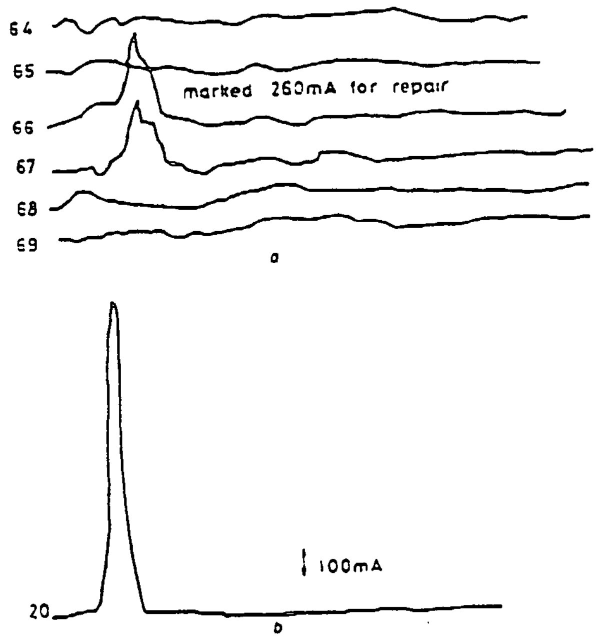

Fig. 8 *Response obtained from the monitoring system*

a The responses derived for slots 66 and 67 indicate minor damage to the tip of the tooth

b 1200 mA response on slot 20 indicates damage towards the bottom of the slot

7 Operator subjectivity

An experiment was devised to determine the extent to which operator subjectivity affects inspection when using the thermographic method and the electromagnetic core imperfection detection method. Nine operators, trained in both techniques, independently examined a surface and a subsurface fault in a test core. Their findings are listed in Table 1 and plotted in Fig. 9.

7.1 Tabulated comparison of test techniques

These tests were carried out in accordance with Reference 1. The techniques presented in Table 2 are listed in terms of their relative strengths and weaknesses. Specifically, in the areas of safety, preparation time and accuracy.

Table 1: Operator subjectivity in test core fault location*

Operator	Thermo-graphic surface	Inspection method subsurface	Electromagnetic core imperfection detection method* surface	subsurface
1	10.2°C	Not located	10.0 C	11.5 C
2	9.8°C	Not located	9.4°C	12.0°C
3	9.1°C	Not located	9.6 C	11.6 C
4	9.5 C	Not located	5.7°C	13.0 C
5	6.2°C	Not located	10.3 C	13.0°C
6	11.1°C	Not located	10.8 C	12.0°C
7	9.2°C	Not located	9.9°C	11.0°C
8	8.3°C	Not located	9.9 C	11.0 C
9	7.7°C	Not located	10.2 C	13.0 C
	m 31%		8%	8%
	m' 16%		3%	2%

* Readings have been converted into their temperature equivalents for comparison

Note: m is % deviation from mean

m' is % deviation from mean without high and low readings

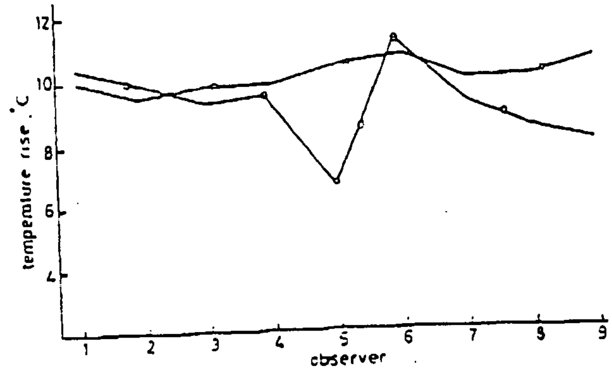

Fig. 9 *Observer objectivity*

O O thermovision technique

▲ ▲ electromagnetic technique

8 Conclusions

There have been several comparisons of methods in the UK and USA and in most cases the correlation has been extremely good. However, when a decision has to be made to carry out a repair which may be deep seated and involves removing coils, it is often desirable to check with both systems, using the ring flux test to verify the fault and using the developed core imperfection equipment further to monitor the repair.

For field operation, a ring flux test is totally impossible and a quick check of a core could be most desirable. In instances where a machine rotor has been delivered at a different time to a stator, an assurance that no transit damage has been incurred is often required. Apart from the desirability of the machine core being fault free, arguments on subsequent insurance claims in the instance of finding a fault on location may also be minimised. However, in most cases, the main criteria is the minimising of down time and keeping capital equipment running for as long as possible. The system described in this paper has been used on numerous large machines and the resultant cost effectiveness has been demonstrated.

Tests carried out on small machines now run into the thousands and the biggest advantage here would appear to be in the saving of repair time and the confidence with which a fault may be located, the repair implemented, and the machine returned to service.

Table 2: Summary chart

		I	II	III	IV	V
Safety (risk)	Man	Some	None	Minimum	Minimum	None
	Machine	Minimum	None	Minimum	Minimum	None
Logistics	Time, hr	24–36	6–8+	24–36	24–36	10
	Material	Extensive	Minimum	Extensive	Extensive	Moderate
	Power required	High	None	High	High	Low
	Personnel	6-10	1+	6–10	6–10	3
Quality of data	Accuracy	Poor	Moderate	Poor	Good	High
	Observer-subjectivity	High	Moderate	Moderate	Moderate	Low
	Permanent record	No	Notes only	Notes only	Limited	Yes
	Subsurface detection	No	No	No	Limited	Yes
	Operational conditions	Flux only	No	Flux only	Flux only	No
Other benefits	Heats core	Yes	No	Yes	Yes	No
	Vibrates core	Yes	No	Yes	Yes	No
	Can test partial core	No	Yes	No	No	Yes

Key.
I = hands-on inspection
II = visual inspection
III = surface treatments
IV = thermographic inspection
V = electromagnetic core imperfection detection

9 Acknowledgments

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10 Reference

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